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Market viability of an avoided wildfire GHG emission accounting framework for California

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This Master's Project

Market viability of an avoided wildfire GHG emission accounting framework for California

By

Justine Bui

is submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Environmental Management

at the

University of San Francisco

Submitted:	Received:
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Justine Bui Date	Tracy L. Benning, Ph.D. Date

Table of Contents

List of Tables

List of Figures

List of Acronyms and Abbreviations

AB 32	Assembly Bill 32
ACR	American Carbon Registry
BLM	Bureau of Land Management
CALFIRE	California Department of Forestry and Fire Protection
CARB	California Air Resources Board
CCX	Chicago Climate Exchange
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CSR	Corporate social responsibility
EU ETS	European Union's Emissions Trading System
FRI	Fire Return Intervals
GGRF	Greenhouse Gas Reduction Fund
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change

IRR	Internal rate of return
MMTCO$_2$e	Million metric tons of carbon dioxide equivalent
MTCO$_2$e	Metric tons of carbon dioxide equivalent
NCS	Natural Climate Solutions
NGOs	Non governmental organizations
NPV	Net present value
REDD+	Reducing Emissions from Deforestation and Forest Degradation, conservation of forest carbon stocks, sustainable management of forests, and enhancement of forest carbon stocks
TAM	Total addressable market
U.S.	United States
USFS	United States Forest Service
VCS	Voluntary Carbon Standard / Verified Carbon Standard
WUI	Wildland urban interface

Abstract

Forests in California and elsewhere are under an increasing threat of uncharacteristically large and severe wildfires. Fuel treatments, such as tree density reduction or prescribed burns, can alter wildfire behavior and potentially reduce risk. An environmental consulting group is currently developing a probability-based greenhouse gas (GHG) emissions accounting framework that would provide tools to quantify GHG benefits of fuel treatments and help fund said treatments through carbon offset credits. This framework is being developed in collaboration with key stakeholders (such as public agencies, carbon offset registries, non-profit organizations, and the private sector) in the western United States. A market assessment is conducted to evaluate the potential for this framework to advance forest-based carbon offset protocols and affect future wildfire severity in California.

Relying on extensive datasets, such as wildfire modeling and vegetation growth simulation models, and delving into such an uncharted industry makes the nature of this accounting framework complicated to build and challenging to execute. Due to the complexities associated with establishing a carbon offset protocol with stakeholders, work on this has been ambiguous, leaving room for this emerging product to be a solid product-market fit. Procured fuel treatments through this framework are an effective addition to a portfolio of solutions in reducing GHG emissions in California, but will require additional monetary investment due to carbon revenue being insufficient in covering the high fuel treatment costs. Overall, this fuel treatment-based carbon offset protocol is a worthwhile endeavor in today's growing carbon offset market and wildfire conditions.

Acknowledgements

First and foremost, I would like to thank my advisor, Dr. Tracy Benning, for her never-ending guidance and flexibility with this project during such unprecedented times. I would also like to thank Dr. David Saah, Jean-Pierre Wack, and Dr. Thomas Buchholz from the Spatial Informatics Group for their direction and insight on the avoided wildfire emissions framework they have been tirelessly developing. Lastly, I would like to thank Whitney Libunao, Austin Davis, and my family for their moral support and encouragement throughout the research and writing process.

Introduction

Forests in California and elsewhere are under an increasing threat of uncharacteristically large and severe wildfires. Fuel treatments, such as tree density reduction or prescribed burns, can alter wildfire behavior and potentially reduce risk. Spatial Informatics Group, an environmental consulting group based in California, is currently developing a probability-based greenhouse gas (GHG) emissions accounting framework that would provide tools to quantify GHG benefits of fuel treatments and help fund said treatments through carbon offset credits. This framework is being developed in collaboration with key stakeholders such as public agencies, carbon offset registries, non-profit organizations, and the private sector in the western United States. This paper addresses the question: What is the market viability of an avoided wildfire GHG emission accounting framework in California? A market assessment is conducted to evaluate the potential for this framework to advance forest-based carbon offset protocols and affect future wildfire severity in California. Procured fuel treatments through this framework are an effective addition to a portfolio of solutions in reducing GHG emissions in California, but will require additional monetary investment due to carbon revenue being insufficient in covering the high fuel treatment costs. Overall, this fuel treatment-based carbon offset protocol is a worthwhile endeavor in today's growing carbon offset market and heightened wildfire conditions, but will require supplementary investment to be successful.

Background and Rationale

Preliminary information is needed to understand the major components of the framework in question, including what the carbon market entails (especially in California), what types of wildfire risk California is facing, what do fuel treatment activities involve, and how all of these factors tie in to the creation of an avoided wildfire GHG emission framework.

Carbon Market

Background on Carbon Offsets

A carbon offset is an accounting mechanism that balances the scales of carbon emissions - an offset credit is equivalent to a greenhouse gas removal enhancement of one metric ton of carbon dioxide equivalent (CO_2e). Carbon offsets are incredibly interesting because they are unlike any other product: buyers cannot tangibly experience a difference in atmospheric carbon associated with their purchase. One would buy a carbon offset to contribute to an activity or project that is working towards mitigating the amount of carbon emissions being released; the purchase of a carbon offset would then mitigate the amount the buyer released. On a larger scale, a company that knows their activities release CO_2 emissions but does not have the time or resources to change their practices may buy carbon offsets to show that they are not contributing to total emissions.

This carbon offset market falls into two broad categories: voluntary and compliance. Voluntary carbon offsets are ones that people and companies can buy at their own discretion, while compliance carbon offsets are purchased to meet legally binding caps on carbon emissions. A big part of the carbon offset world began with the Kyoto Protocol in 2005, an international pact that would act on climate change; one of the keystones of the Protocol was the Clean Development Mechanism (CDM), a global compliance market for offsetting emissions (Irfan, 2020). The European Union's Emissions Trading System (EU ETS) is one example of policy being used to combat climate change and reduce greenhouse gas emissions; it is the world's first major compliance carbon market and remains one of the biggest ones. Europe launched the EU ETS in 2005 to trade CDM offsets, but while attention focused on the compliance market, innovation was given room within the voluntary market where new methodologies could be developed and tested. The framework addressed in this paper will be solely in the realm of voluntary carbon offsets with brief comparisons to compliance carbon offsets throughout.

The voluntary market has been used as both a tool for individuals to reduce their carbon footprints and as a way for corporations to take large scale action against greenhouse gas emissions. Throughout the early 1990s and early 2000s the market was slowly evolving and experimenting; standards were created and voluntary platforms like the Chicago Climate Exchange (CCX) emerged. The CCX was initially developed in 2003 as a pilot program for the United States to reduce, audit, register, and trade greenhouse gas emissions, but it soon turned into the world's first large-scale platform for registering and trading voluntary offsets (Donofrio et al., 2019). Most voluntary carbon offsets are tracked by registries such as the American Carbon Registry (ACR), the Climate Action Reserve, and Verra (formerly Verified Carbon Standard). Registries are able to provide additional levels of accountability and security when it comes to issuing, holding, and acquiring credits; they are a source of available credits for sale but do not actively market them. For example, the American Carbon Registry requires that there be independent third-party validation and verification for all of the voluntary carbon offset projects that go through them, following their own ACR Validation and Verification Standard (American Carbon Registry, 2020). As voluntary carbon market activity continued to innovate, it also continued to increase with new major sources of demand materializing.

In the late 2000s the most common project types for voluntary offsets were in forestry and land-use sequestration, renewable energy, and industrial gases. Every single year the market value continued to rapidly increase. By 2010 new projects such as methane destruction projects and clean cookstoves were introduced and the Voluntary Carbon Standard (VCS), also known as the Verified Carbon Standard today, became the standard for certifying carbon emissions reductions (Donofrio et al., 2019). This standard is administered by the non profit organization Verra. Throughout the 2010s there became a growing interest in nature-based solutions, which was reflected in increased transactions of VCS-certified forestry credits, and scaling up community-based sustainable development. Buyers were looking more at generating positive social impact in addition to reducing emissions.

As a successor to the Kyoto Protocol, the Paris Agreement was finalized in late 2015 and was a clear sign that many international governments recognized a need for urgent action on climate change. The Kyoto Protocol only had emission reduction targets for the wealthier countries, and those countries mutually agreed on their respective share of contributions, but the Paris Agreement pushed that even further by encouraging all countries to make contributions and independently decide on the extent of their contributions (Webb and Zakir, 2019). By 2015 the overall volume in offset sales had increased ahead of the Paris Climate talks, but the overall market value had declined slightly; many buyers were looking at lower cost offsets generated by wind farms which overtook REDD+ (Reducing Emissions from Deforestation and Forest Degradation, conservation of forest carbon stocks, sustainable management of forests, and enhancement of forest carbon stocks) as the most-transacted project type that year (Donofrio et al., 2019). Unfortunately, after the Paris Agreement, there was a large drop in volume and market value as voluntary markets entered a limbo phase. By 2018, forestry and land use was the clear project type leader in both transactions and issuances, thus a shift to Natural Climate Solutions (NCS) had begun.

Natural Climate Solutions

The increased volume in forestry and land use offsets can be attributed to a newfound buyer enthusiasm for Natural Climate Solutions. This could be because of a shift in buyer preferences or because of the expansion of domestic policy into activities that were previously covered in the offset space. Natural Climate Solutions are activities that reduce emissions by financing improved management of forests, farms, and natural ecosystems. They have been a foundational part of the voluntary carbon offset market since their beginning in the 1980s but within the past two years they have gained immense popularity for a variety of reasons. In 2017 the Proceedings of the National Academy of Sciences published research that showed that the climate mitigation potential of Natural

Climate Solutions has been vastly underestimated. Then, the following year, the Intergovernmental Panel on Climate Change (IPCC) Lands report identified carbon sinks, especially from NCS, as critical to meeting the Paris Climate Agreement's target of keeping global warming below 2 degrees Celsius (Donofrio et al., 2019). From there non governmental organizations (NGOs) and United Nations agencies launched many awareness-raising campaigns around NCS and media outlets increased coverage of them, especially projects that involved tree-planting. Natural Climate Solutions are becoming even more important nowadays due to the fact that many other strategies that have been suggested or piloted to create "negative emissions" rely on technologies that do not yet exist as cost-effective or scalable solutions (Marvin et al., 2018).

Nowadays, a large majority of forest carbon offset transactions occur in the voluntary market; the carbon offset prices in the voluntary market tend to highly correlate with what is expected to occur with climate change agreements and its growing rigidity (Covell, 2011). Table 1 shows the transacted voluntary carbon offset volume, value, and weighted average price by project category between 2017 and 2019 from Forest Trends' Ecosystem Marketplace, with forestry and land use having the largest increase in volume and value. As you can see in the table, the Forestry and Land Use category also tends to have one of the higher average prices each year - this may be due to the large range of co-benefits they can deliver which increases the perceived benefits, compared to a category like Renewable Energy which has more straightforward benefits.

Table 1. Transacted Voluntary Carbon Offset Volume, Value, and Weighted Average Price by Project Category, 2017, 2018, and 2019. Adapted from Forest Trends' Ecosystem Marketplace

	2017			2018			2019		
	Volume ($MtCO_2e$)	Average Price	Value	Volume ($MtCO_2e$)	Average Price	Value	Volume ($MtCO_2e$)	Average Price	Value
Forestry and Land Use	16.6	$3.4	$63.4M	50.7	$3.2	$171.9M	36.7	$4.3	$159.1M
Renewable Energy	16.8	$1.9	$31.5M	23.8	$1.7	$40.9M	42.4	$1.4	$60.1M
Waste Disposal	3.7	$2.0	$7.4M	4.5	$2.2	$10.0M	7.3	$2.5	$18.0M
Household Devices	2.3	$5.0	$11.8M	6.1	$4.8	$29.5M	6.4	$3.8	$24.8M
Chemical Processes / Industrial Manufacturing	2.6	$1.9	$4.9M	2.5	$3.1	$7.9M	4.1	$1.9	$7.7M
Energy Efficiency / Fuel Switching	1.1	$2.1	$3.3M	2.8	$2.8	$7.8M	3.1	$3.9	$11.9M
Transportation	0.1	$2.9	$0.2M	0.3	$1.7	$0.5M	0.4	$1.7	$0.7M

Although forestry and land use offsets continue to increase and have positive climate impacts, these projects can still be proven to be financially impractical for many reasons (Covell, 2011):

- Forest carbon projects tend to be excluded from compliance markets and have relatively low prices in the voluntary markets
- Complex carbon accounting methodologies can rule out many projects' eligibility to be certified under accepted standards
- Project development and transaction costs can be very high (especially for small-scale projects)
- The carbon market involves high levels of uncertainty and risk in discounted project value

Carbon Accounting

At its most basic level, carbon emission offset credits are tradable certificates or permits that represent the right to emit a designated amount of carbon dioxide or other greenhouse gas if there are activities being done elsewhere that reduce those greenhouse gas emissions; this means that offsets can theoretically be generated by projects that reduce potential emissions from wildfires. The offsets produced can be traded, leased, banked for future use, or sold to other entities that need to provide emission offsets (Saah et al., 2012). The objective of GHG accounting is to quantify the amount of CO_2 and other GHGs that are cycling between carbon pools, especially the amount of GHGs released into the atmosphere within a given time period (CARB, 2018). Many state, federal, and international organizations have developed reporting programs and protocols for carbon accounting which has increased the popularity of carbon offsets, but has also made it difficult to be consistent, comparable, and scientifically based. Figure 1 shows how the US Department of Agriculture and the US Forest Service interpret the forest sector carbon cycle. Model selection, uncertainty, and general agreement on definitions of carbon pools have all contributed to the confusing world of carbon accounting.

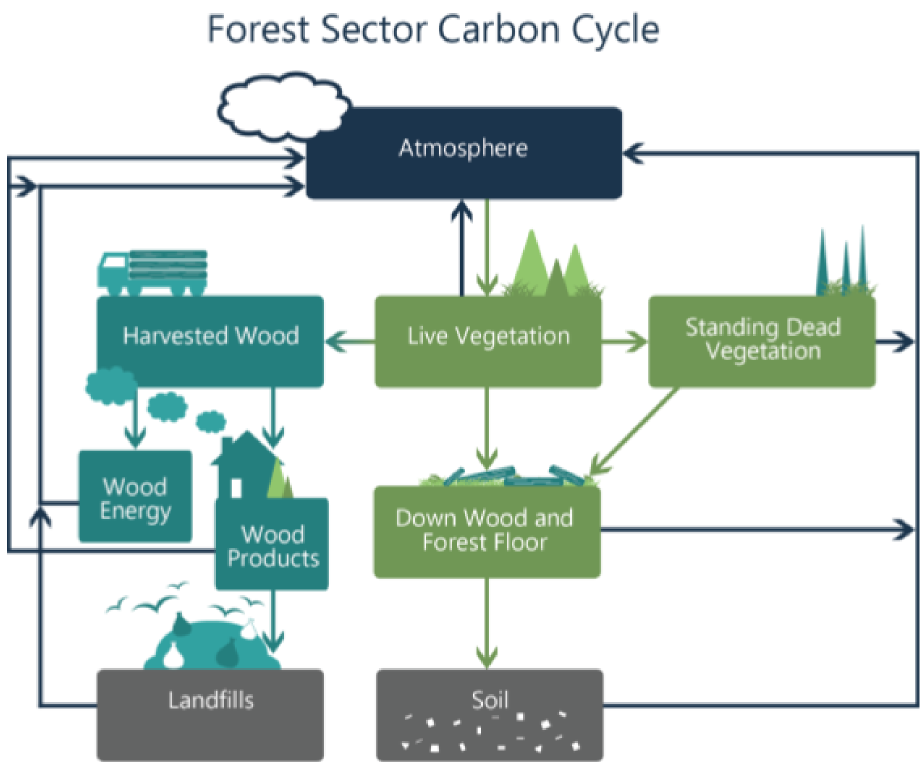

Figure 1. The forest sector carbon cycle includes forest carbon pools and carbon transfer between pools. Source: US Department of Agriculture and US Forest Service

Good accounting practices should include principles such as accuracy and precision, comparability, completeness, conservative estimations, consistency, relevance, and transparency (Saah et al., 2012). To establish a reliable forest carbon accounting, discrete accounting areas and accounting for carbon stocks, emissions, and emission reductions must all be determined.

Skepticism around Carbon Offsets

The biggest issue with dealing in carbon offsets is that many of them that are sold do not deliver on the promise of emission reductions. Because there are many different offset programs that have their own standards and practices, it is difficult to regulate and uphold the market. One big example of failure to deliver is the United Nation's REDD+, one of the most prominent international offset programs that was first formed in 2005 (Irfan, 2020). This program's goal was to reduce emissions associated with deforestation and restore natural areas - they did this through helping wealthier countries stay within their carbon caps by routing funding to developing countries where most of these forests are actually located. Their biggest struggle was in places like the Amazon, where pressures to cut down the rainforest were higher than the payments being given to protect it. Many buyers had no idea deforestation continued; they were able to believe that their offset purchase was actually working and could continue to emit CO_2 guilt-free.

Another issue many have with carbon offsets is the idea that companies will purchase them as a way to absolve themselves from working on reducing emissions internally. Fortunately, through surveys conducted by Ecosystem Marketplace, it has been found that the companies who put an actual price on carbon and use voluntary offsets to reduce their emissions tend to be the most aggressive at reducing emissions internally, using the offsets as a way to deepen their broader reduction goals (Donofrio et al., 2020).

California's Carbon Market

California has some of the world's strongest environmental protections and has taken upon themselves to endorse 2020, 2030, and 2050 goals to reduce greenhouse gas emissions across its economy (CARB, 2017). California's carbon market is unique in the United States because it is explicitly outlined within California's climate plan through the Cap-and-Trade Program. The Cap-and-Trade Program's goal is to "reduce greenhouse gas (GHG) emissions from major sources (covered entities) by setting a firm cap on statewide

GHG emissions while employing market mechanisms to cost-effectively achieve the emission-reduction goals" (CARB, 2012). This means that California has a compliance market embedded into its government policies that can deliver economic and environmental benefits to landowners, farmers, and foresters that participate in documenting emissions reductions and generating sellable credits. This compliance market also has the potential to spur innovation within these sectors of the economy and help develop the voluntary market in California as well.

Assembly Bill 32

According to California's Global Warming Solutions Act of 2006, also known as Assembly Bill 32 (AB 32), there are two long-term goals for pollution reduction: reduce GHG emissions to 1990 levels by 2020 and reduce pollution 80% below those levels by 2050 (Environmental Defense Fund, 2012). According to AB 32, all offset credits must be "real, permanent, quantifiable, verifiable, enforceable, and additional" (CARB, 2019). AB 32's emission limit goal for 2020 was to get California to not emit more than 431 MMT CO_2e, and as you can see in Figure 2, based on most recent data from the California Air Resources Board, in 2016 California's GHG emissions dropped below the 2020 GHG Limit and have remained below the 2020 GHG Limit since that time.

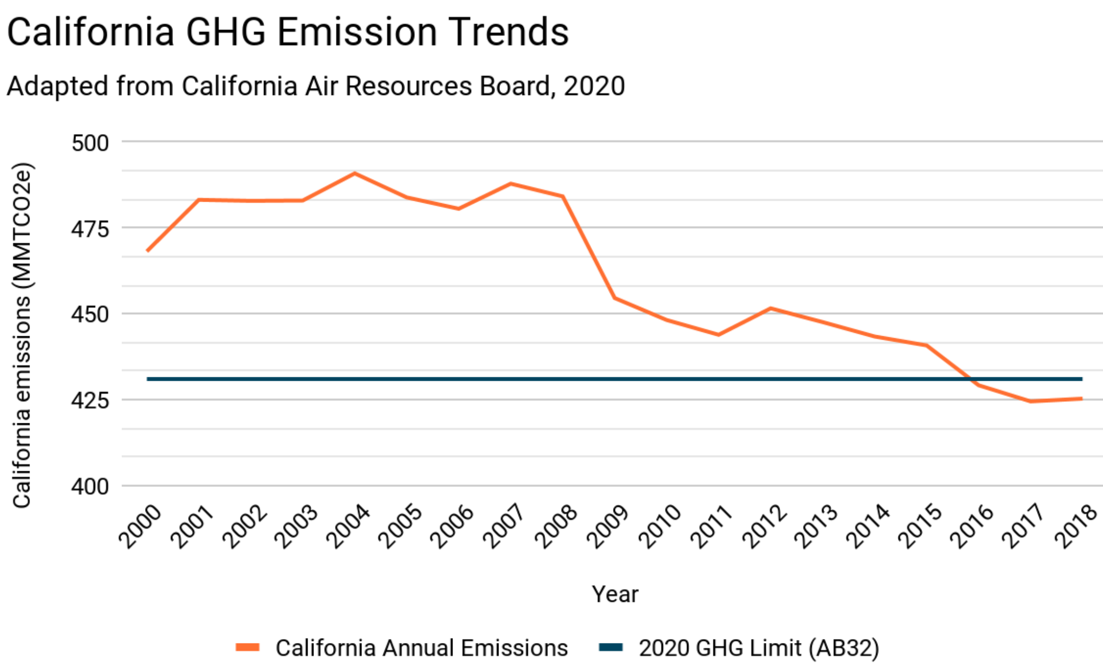

Figure 2. California's annual GHG emissions from 2000 to 2018. The 2020 GHG Limit required by the California Global Warming Solutions Act (Assembly Bill 32) is 431 MMT CO_2e. Source: CARB, 2020

The Cap-And-Trade Program

The Cap-and-Trade Program is responsible for achieving around 1/5th of the reductions outlined in Assembly Bill 32 for 2020 and truly is the cornerstone of that act. This program began in 2012 and focused on electricity generation and large stationary sources of GHG emissions, but then expanded in 2015 to fuel distributors to address emissions from transportation fuels (CARB, 2012). Major GHG-emitting sources, such as electricity generation, fuel distributors, and large stationary sources (e.g. refineries, production facilities, and food processing plants) that emit more than 25,000 metric tons of carbon dioxide equivalent ($MTCO_2$e) per year will be the ones who have to comply with this Cap-And-Trade Program (CARB, 2012). The main benefit of having these regulations is that they limit the number of offsets that capped entities can use to meet their compliance obligations to 8%, which means that these capped entities, usually the largest polluters, are pushed to make the majority of their reductions on their own, either directly or on-site (Environmental Defense Fund, 2012). Direct reductions are likely to be less costly, compared to every entity using its entire 8% of offsets, which would make it more economical for them to meet their obligations by doing activities such as improving energy efficiency or switching fuels (Environmental Defense Fund, 2012). This advances market mechanisms that help develop cost-effective ways to reach emission-reduction goals (CARB, 2012). If a company is not able to meet the program's major compliance requirements, they would be subject to strict penalties that are determined by the California Air Resources Board based on the specific circumstances (CARB, 2012). Forest conservation activities in particular have been instrumental in reducing greenhouse gas emissions through California's Cap-and-Trade Program (Marvin et al., 2018).

In total, about 80% of all GHG emissions in California is covered by the Cap-and-Trade Program. Since California implemented a lot of its major climate programs, including the Cap-and-Trade Program, it's economic growth has consistently dominated the rest of the country; California's average annual growth ranks second in the country since Cap-and-Trade went into effect in 2012. It is estimated that by 2030, California's economy is projected to grow $3.4 trillion (CARB, 2017).

California's Compliance Offset Protocol - US Forest Projects

California has adopted six compliance offset protocols that can be used to generate offset credits:

- U.S. Forest Projects
- Livestock Projects
- Ozone Depleting Substances Projects
- Urban Forest Projects
- Mine Methane Capture Projects
- Rice Cultivation Projects

The main protocol of relevance here is the U.S. Forest Projects protocol; this program is just a small part of the Cap-and-Trade program that incentivizes reductions or sequestration of GHG in sectors that are not covered by the cap. Under the U.S. Forest Project protocol there are three main project types: 1) Improved Forest Management, 2) Avoided Conversion, and 3) Reforestation. To qualify as a forest offset project, the project must be a planned set of activities that either increases carbon storage in trees or prevents the loss of carbon stored in trees, compared to what would have occurred in the forest without project activities (CARB, 2019). Every project in this protocol must be verified by a California Air Resources Board-accredited third-party verifier which requires site visits for sample remeasurements to confirm the accuracy of the inventory. In 2017 forest offset projects in California generated 19 million metric tons (MMT) CO_2e in compliance offset program credits registered with CARB (Forest Climate Action Team, 2018). As of 2019, California has issued the second most Forest Offsets across the United States at a count of over 23 million, right behind Alaska at around 26 million and ahead of Arizona issuing over 10 million offsets (CARB, 2019).

Governor Jerry Brown released an Executive Order in September 2018 that set an additional ambitious goal for California: make the state climate neutral, or even carbon negative, by 2045. To achieve this ambitious goal, California will need to work more on preventing emissions and enhancing carbon sequestration through land-based strategies (Marvin et al., 2018).

Wildfire Risk

Fire has been a natural part of California's ecosystems for an incredibly long time; it helps germinate seeds for certain tree species, clear dead biomass so living trees have more room to grow, replenishes soil nutrients, and reduces the accumulation of fuels that could increase the severity of wildfires (CARB, 2020). It is estimated that 20 million acres of California forestland are under high wildfire threat and would greatly benefit from fuel treatments to reduce the risk and severity of wildfire (Forest Climate Action Team, 2018). To develop a quantitative risk assessment for an area like California, there are many different factors that have to be evaluated such as: values of human-created property like buildings and roads, and environmental and ecological effects, all of which need to be using a common currency which is not always straightforward (Finney, 2005). Although property can be easily appraised in terms of money, ecological impacts can have considerable value physically but cannot be quantified monetarily. An incredibly important aspect of pursuing a risk assessment is recognizing how variable the behavior of fire is, and how decisions to be made are necessary to deal with fire impacts (Finney, 2005).

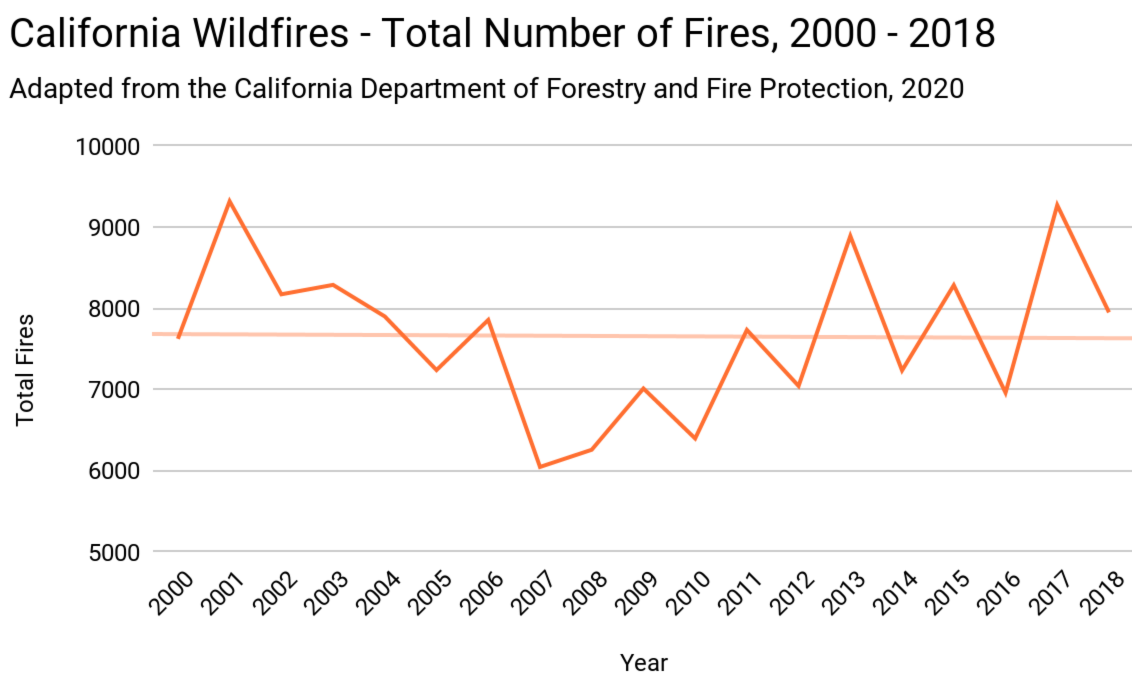

Figure 3. Total number of California wildfires between 2000 and 2018. The number of fires greatly varies between years, but the trendline tends to stay relatively flat. Source: CALFIRE, 2020

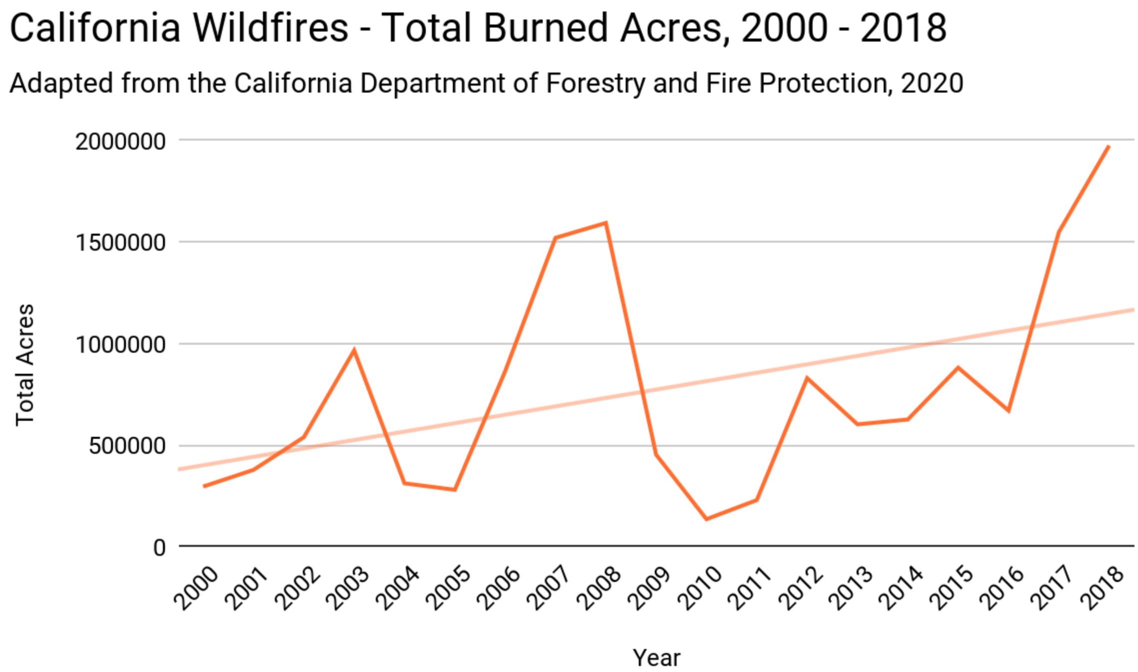

Figure 4. Total number of burned acres in California from wildfires. The trendline of the number of burned acres continues to increase. Source: CALFIRE, 2020

As you can see in Figure 3 from the California Department of Forestry and Fire Protection (CALFIRE), the total number of fires greatly varies between years, but the trendline tends to stay relatively flat. Looking at those same years in Figure 4 shows us that although the total number of fires is staying consistent on average, the total number of burned acres in California continues to increase. This tells us that wildfires in California are becoming larger and more severe. Figure 5 gives us a visual snapshot of the amount of burned land from fires in California in 2017, totaling around 1.2 million acres burned (CALFIRE, 2017); at the time this was the largest and most destructive fire season California had to deal with, until 4.3 million acres were burned in 2020.

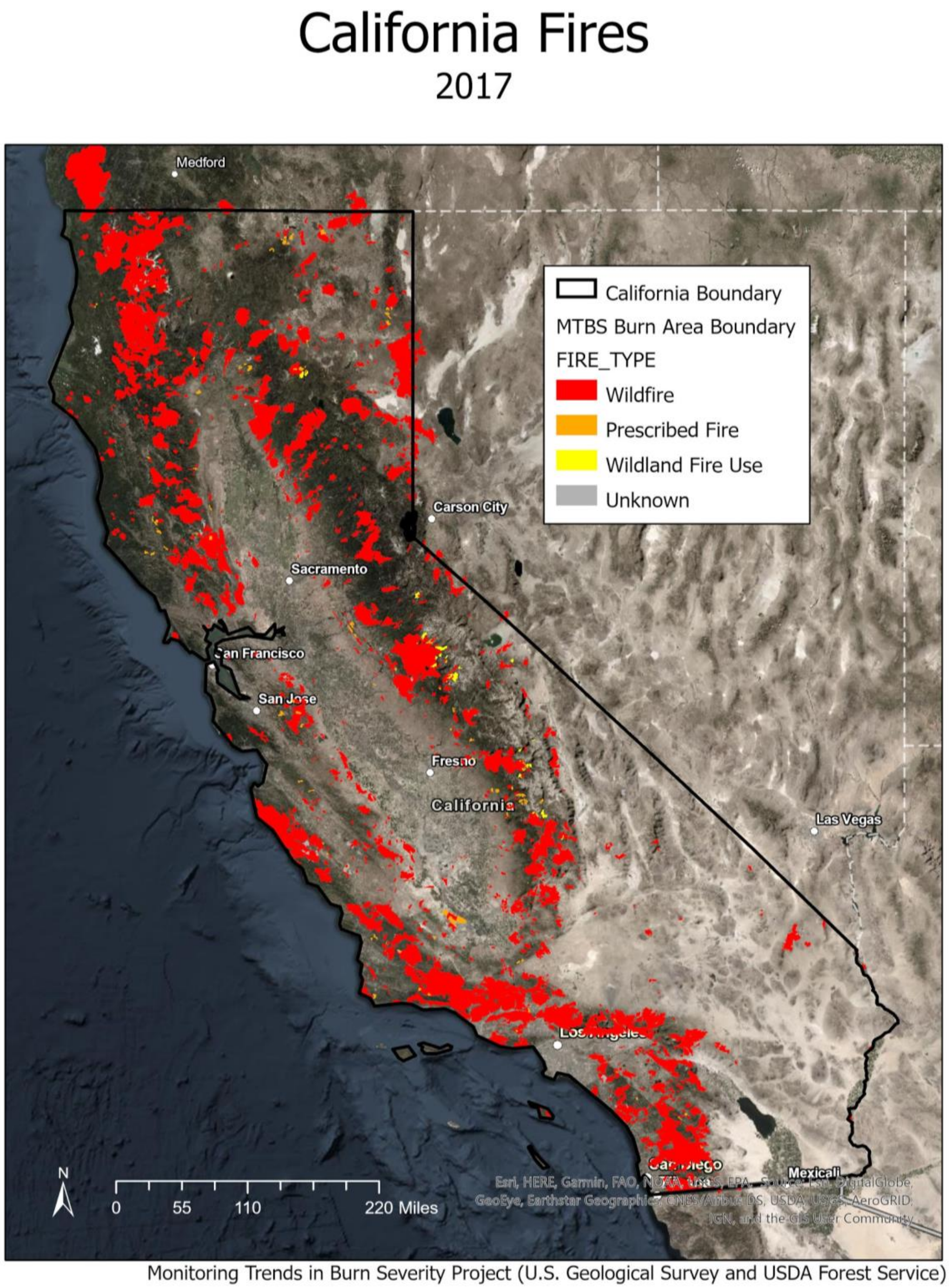

Figure 5. Fires in California in 2017. Data source: U.S. Geological Survey and USDA Forest Service

Some options to reduce fire risk in wildland and urban areas include (Finney and Cohen, 2003):

- Implementing fuel treatments immediately adjacent to structures, which helps change the behavior of the fire relative to the ignition of structures
- Changing the properties of structures, which improves the structures' response to fire behavior

Fuel Treatments

Fuel treatments are a means to limit the size and intensity of wildfires; fuel treatment activities include mechanical (crown thinning, thinning from below followed, rotary mastication) and prescribed fire. Fuels in this context are the live and dead biomass that end up being burned in a wildland fire. Fuels are then classified into two categories: surface fuels and canopy fuels. Surface fuels are the dead woody biomass and live or dead shrubbery that can be found on the ground of the forest. Canopy fuels are the aerial biomass that include things like tree branches, foliage, mosses, and hanging dead material like needles. Fuel treatments are designed to alter fuel conditions so that wildfires can be less difficult and destructive.

Fuel treatments generally have a life expectancy of 10-25 years with simulations suggesting that treatments on as little as 1% of land annually could reduce the area subject to severe wildfire by 50% over a 20 year period (Campbell et al., 2012). They are also able to reduce the impact of future stress events on remaining trees which will allow them the opportunity to continue to sequester and grow; within a decade or two of treatment the remaining trees are more resilient and will capture the carbon originally lost from the removal of biomass (Forest Climate Action Team, 2018). Strategically locating fuel treatment activities have been shown to maximize the treatment benefits while minimizing the area needing to be treated (Chiono et al., 2017). Retreatment is generally required within 20 years of the initial treatment to maintain stand health and fire risk benefits, and fortunately retreatment involves removing much less carbon than the first treatment (Forest Climate Action Team, 2018). Retreatment is usually applied through prescribed fires in which the amount of carbon that is removed is usually sequestered back into the remaining trees within 10 years (Forest Climate Action Team, 2018).

Although many people believe and suggest that fuel treatments can help reduce wildfire extent or make it easier to suppress, it is important to note that this should not be the primary goal of fuel treatments; instead, treating fuels should focus on reducing the severity and intensity of wildfires. Severity in this case can be measured by the amount of damage done by a fire or how the post-fire environment looks (Veblen, 2003). This distinction between reducing extent and reducing severity is important because fuel treatments do not "fire proof" areas; ignition sources are widespread and cannot be fully eliminated from a landscape. Ignition sources are generally not limiting; even with a little or a lot of fuel sources, extreme weather conditions or dry lightning (a common issue in the western United States) can still cause fires to occur and spread. The western United States has seasonally dry and hot conditions that can easily cause biomass, whether it is living or dead, to burn. For federally managed public lands in the United States, 99% of all reported fires are suppressed (Finney, 2005). Unfortunately, fire suppression can potentially lead to continued fuel accumulation which would lead to more troublesome conditions (Reinhardt et al., 2008). Environmental impacts that can be expected from suppression operations include trees falling and cutting firelines, helispots, or safety zones; chemical contamination of soil or water through retardant drops or refueling of equipment; and soil disturbance from heavy equipment (Ingalsbee, 2003). In addition to the physical impacts of fire suppression, it has been found that suppression costs are positively correlated with fire sizes and areas burned, suggesting that fuel treatments to reduce fire size could lead to reduced suppression costs (Thompson et al., 2013). As seen in Figure 6, fire suppression costs have been on the rise, leading to millions of dollars being spent on fires after they happen, and not before to prevent them. Extreme wildfire behavior could even render the most intensive fuel treatments ineffective, so rather than designing treatments to prohibit or suppress fires, designing treatment to minimize fire effects would be more productive.

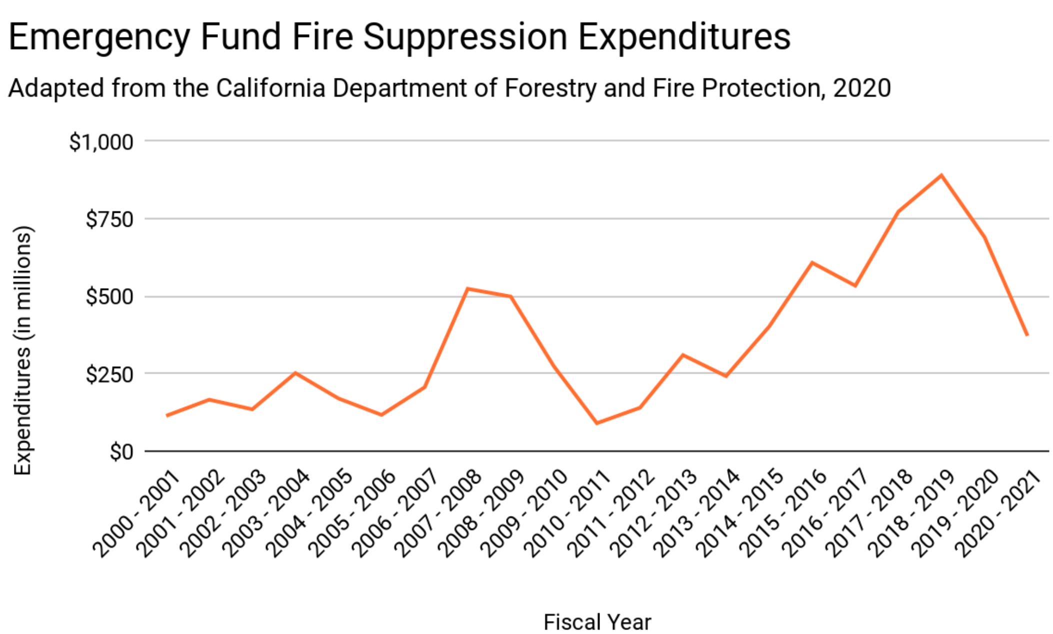

Figure 6. Emergency Fund Fire Suppression Expenditures in California over fiscal years starting from 2000 up to expected expenditures in 2021. Source: CALFIRE, 2020

Fuel treatment use has been rationalized by two recent realizations: 1) recent and well known failures of fire suppression have led to great destruction of wildlands and developed areas where fire conditions are becoming even more extreme, and 2) people are now recognizing that the extreme nature of fires are being further exacerbated by human influence (Finney and Cohen, 2003).

The effectiveness of fuel treatments in reducing fire severity is generally agreed upon and, depending on the fuel treatment type, could serve additional goals such as restoring native species composition, protecting vegetation from insect and disease outbreaks, and supplying wood products and its associated work opportunities (Campbell et al., 2012). Additional benefits from fuel treatments include improved wildlife habitat, water resource protection, greater resilience of recreational lands, and improved public safety (Forest Climate Action Team, 2018). Overall, research has shown that the large-scale application of fuel treatments such as prescribed fire and mechanical thinning can address the underlying issues of declining forest health and increased fire risk (Toman and Shindler, 2003).

Carbon Impact

Forest ecosystems are an incredibly important part of the carbon cycle – they take in carbon dioxide from the atmosphere through the process of photosynthesis and store carbon in their biomass and soil through the process of sequestration. Through the many cycles of a forest such as growth, disturbance, and management activities, carbon is stored and released at varying rates. The California Air Resources Board’s Natural and Working

Lands Greenhouse Gas Inventory shows us that California's natural and working lands (rangeland, forests, woodlands, wetlands and coast areas, grasslands, shrubland, farmland, riparian areas, and urban green space) are a net GHG source, which means they are losing more carbon than they can sequester; the biggest reason for this carbon loss is due to wildfires (CARB, 2019). Between 2001 and 2010, of the estimated 150 million metric tons of carbon lost from California forests, approximately 120 million metric tons of that carbon was lost from wildfires (Forest Climate Action Team, 2018). Fires and fuel-reduction treatments can affect carbon stocks through high-severity fires that can lead to loss in soil fertility or general disturbance events that can lead to changes in tree density (Campbell et al., 2012). Smaller trees tend to be more vulnerable to fires, pest outbreaks, and other disturbances that can cause unstable carbon stocks within a forest (Forest Climate Action Team, 2018). The larger the tree, the more carbon it can store, so while smaller trees are disproportionately more vulnerable to fire mortality, the act of thinning small trees combined with frequent burning could eventually increase biomass and carbon stock by maintaining the larger trees (Campbell et al., 2012).

Both fuel reduction treatments and wildfires remove carbon from a forest - Table 2 shows that treatment activities can lose between 10-30% above ground carbon on average, whereas wildfires consume an average of 12-22% of the above ground carbon in comparable fire-suppressed forests (Campbell et al., 2012). This begs the question: are fuel reduction treatments worth implementing to reduce wildfire severity if aboveground carbon is lost either way? The answer is yes. Fuel treatments are useful in reducing the amount of combustion in a subsequent wildfire, and if the treatment is implemented at a greater intensity, the greater the reduction will be of the future combustion (Campbell et al., 2012).

Table 2. Above ground carbon losses associated with fuel reduction treatments in semiarid conifer forests in the western US. Source: Campbell et al., 2012	
Treatment	**Above ground carbon losses**
Prescribed fire only	10%
Thinning only	30%
Thinning followed by prescribed fire	50%

Reducing wildfire severity through prescribed fires and the removal of combustible surface fuels ahead of time usually allows larger trees holding more carbon stock a higher chance to survive (Campbell et al., 2012). Figure 7 shows how random disturbances on untreated land could have variable effects on carbon stock, whereas frequent low-severity disturbances such as prescribed fires and thinning would only affect small trees and thus allow a steady state of carbon stock to continue.

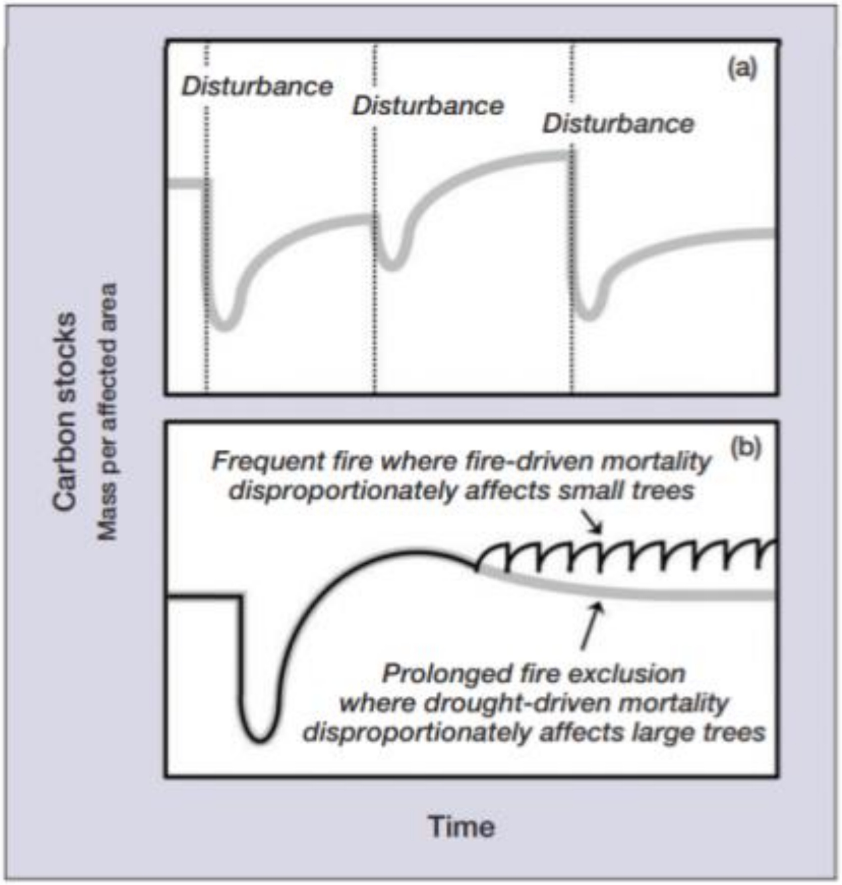

Figure 7. Hypothetical examples of how disturbances could initiate alternate steady-state C stocks. (a) Illustration of what C stocks may look like if long-term successional trajectories depended on seed availability at the time of fire than they were on fixed site conditions. (b) Illustration of how frequent fires could shift mortality away from larger trees and toward smaller trees, thus increasing steady-state C stocks. Source: Campbell et al., 2012

Proper forest management in the context of wildfire and other natural disturbances can potentially have a significant impact on the United States forest carbon balance (Ager et al., 2010). From a purely carbon perspective, fuel reduction activities can reduce potential emissions through the removal of surface and canopy biomass, decreasing the probability, extent, and severity of wildfires. Carbon emissions that are associated with wildfires are then potentially mitigated by fuel treatments due to the lower intensity of the fire. Management and thinning of forests can also naturally stimulate forest growth which could result in a higher uptake of atmospheric carbon. Fuel management increasing carbon storage over space and time is dependent on the ability of the fuel treatments to increase achievable biomass (Campbell et al., 2012). Researchers have also found that treated forests have a higher capability of sustaining carbon sequestration rates under hotter and drier conditions such as those are soon coming with climate change (Forest Climate Action Team, 2018). A larger range of climate conditions for our forests is essential for continued carbon storage and surviving negative climate change impacts. Although it is not likely that fuel treatments can increase carbon storage through the reduction of future combustion, more work is needed to be done to determine if fuel treatments decrease carbon storage long term; in the meantime the non-carbon benefits of fuel treatments still make them worthwhile to implement.

Types of Treatments

There are a variety of fuel treatment activity types that are mapped out in Figure 8, but there are three overarching categories of fuel treatment types that are likely to be implemented into the framework: understory clearing, thinning, and prescribed fire.

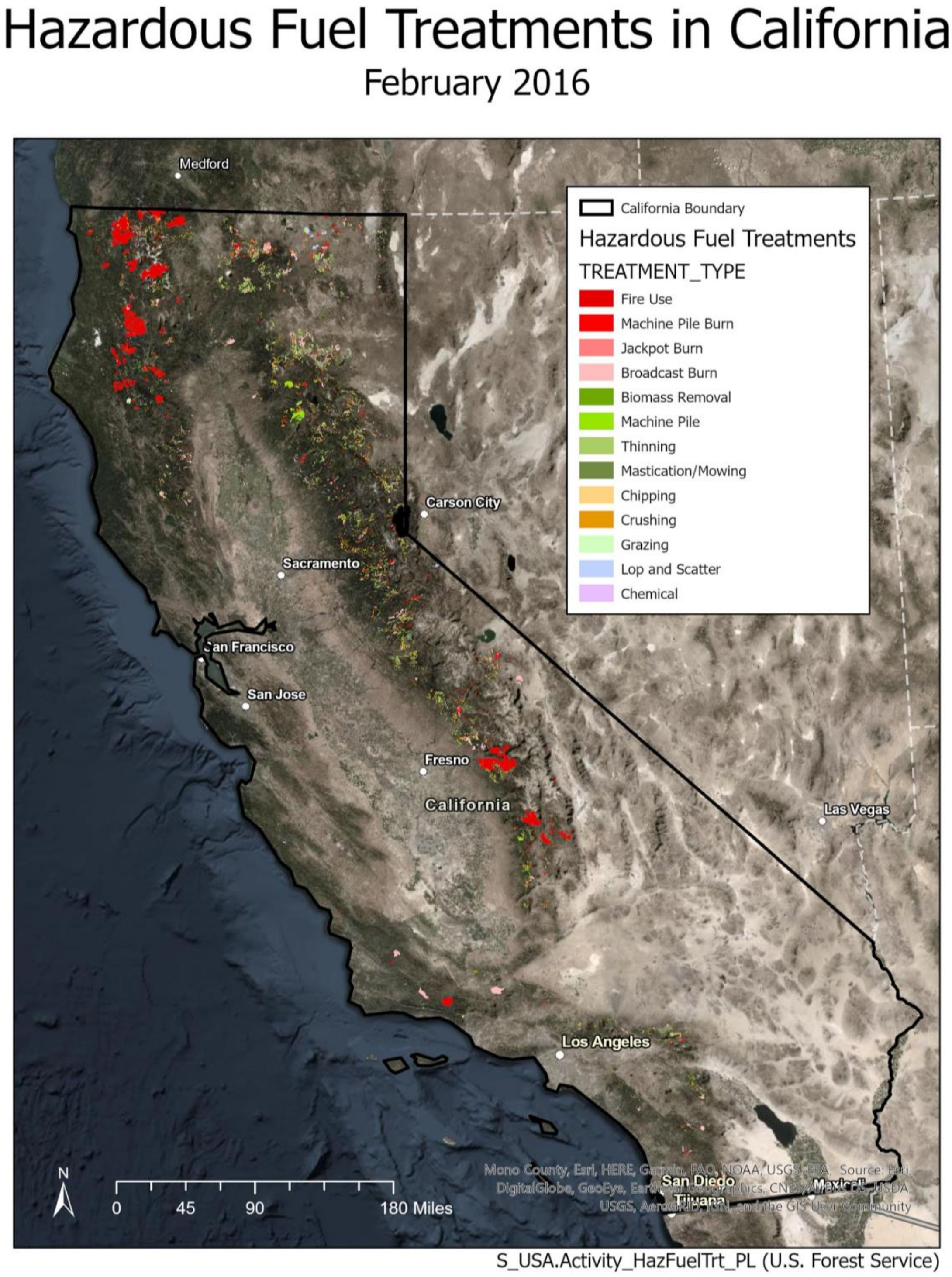

Figure 8. Types of hazard fuel treatments applied in California in February 2016. Data source: U.S. Forest Service

Understory clearing

Understory clearing entails removing forest understory biomass such as dead debris. This treatment impacts above-ground live understory vegetation and dead biomass, but the loss of stored carbon from these sources eventually accrue within the year of implementation, enhancing the net forest carbon accumulation and reducing the impact of high-severity wildfires for 20 years without any additional treatment (CARB, 2019).

Thinning

Thinning is a fuel treatment that entails removing about 20% of the live canopy and standing dead trees to reduce forest fire risk (CARB, 2019). The harvest that comes from this practice could be used for forest products and bioenergy production. In the same way that understory clearing does, thinning allows for the enhancement of net forest carbon accumulation and helps reduce the severity of wildfires for 20 years without additional treatment (CARB, 2019).

Even if fuel treatments lead to short term loss of forest biomass, it can be argued that it is more than made up for by the reduction of future wildfire emissions which is why thinning practices that lower the severity of wildfires should be given incentives instead of penalization in carbon accounting programs (Campbell et al., 2012). Forest thinning aligns itself with four high priority environmental and societal concerns that forest managers face today: fire hazard, economic stimulus, forest health, and climate change mitigation (Campbell et al., 2012).

When it comes to public concern surrounding mechanized thinning, little research has been conducted; concerns over this type of fuel treatment range from potential ecological effects and aesthetic impacts to doubts around whether or not this treatment will produce a sufficient amount of marketable timber to offset the operational costs (Toman and Shindler, 2003). Some even believe that mechanized thinning is a way for forest managers to continue harvesting under the guise of treating fuels to reduce fire hazard (Toman and Shindler, 2003). These perceptions are why communication of accurate information plays an important role in decision making and forest management practices; the public should know what are the goals, what the impacts will be, and who will be affected so they are equipped with the right knowledge and are supportive of fuel treatment practices.

Prescribed Burning

Prescribed burning is a treatment that burns understory vegetation and piled or scattered debris with the intent of sparing the majority of live trees (CARB, 2019). Implementing prescribed burning affects the carbon found in above-ground live vegetation and dead biomass, but, similar to understory clearing and thinning, this treatment ends up enhancing net forest carbon accumulation and can reduce the severity of wildfires for up to 20 years without any additional treatment (CARB, 2019). Although the effectiveness of this treatment in reducing wildfire severity is well documented, there is a real lack of data on its effectiveness in reducing GHG emissions compared to emissions from wildfires (Defosse et al., 2011).

Prescribed fires were in practice at least 100 years ago in the western United States; in the past they used “light burning” in the forests of the southern Cascade Mountains and northern Sierra Nevada of California to modify potential wildfire behavior (Stephens and Moghaddas, 2005). Federal managers and scientists of this time did not support light burning because of the potential for the fire to escape and the creation of tree injuries that could allow heart-rot fungi to enter (Stephens and Moghaddas, 2005). At the time, the idea of eliminating light burning was thought to allow higher yields of wood products. We now know that particulate pollution from Western wildfires are significantly high, and that prescribed burning actually produces less particulate emissions than wildfires (Forest Climate Action Team, 2018).

Prescribed burning involves the highest level of public concern among the different types of fuel treatments; many associate prescribed burning with:

- Risk of the fire escaping and endangering public safety or private property
- The health impact smoke has on air quality
- The ecological impact on wildlife, vegetation, and water quality
- The economic risk such as losing valuable timber
- And the loss of aesthetics such as scenery and recreational use of the land

Despite these persistent concerns, public attitudes towards prescribed burning have evolved towards greater acceptance as forest management agencies have improved their communication strategies of the risks and factors involved in this treatment (Toman and Shindler, 2003).

Biomass Utilization

Fuel treatments that remove forest woody biomass could then use that biomass for other higher value purposes and products such as electricity and heat, transportation fuels, chemicals, and physical products used directly in many industries (Saah et al., 2012). This type of fuel treatment offers higher economic incentive to implement, but unfortunately faces many obstacles such as limited access to funding, distance from biomass utilization facilities, public perception of the effects of biomass removal, and scientific evidence to support the sustainability of these types of activities (Saah et al., 2012).

If there is not a method available to utilize biomass, the excess biomass from mechanical treatments are usually either masticated and put back onto the forest floor, or piled and burned (Forest Climate Action Team, 2018). Masticating excess biomass and putting it back onto the forest floor can help recycle nutrients and offer a short-term carbon source, but it can also potentially increase fire intensity for the first couple of years until the material decays (Forest Climate Action Team, 2018). Pile burning immediately releases carbon emissions into the atmosphere, but can be necessary to remove thinned materials in areas where there is no market for the materials or the costs to remove and transport the materials are too high (Forest Climate Action Team, 2018). This is why there is a need for a wider range of alternative disposal methods of biomass.

Disadvantages of Fuel Treatments

Since fuel treatments inherently remove stored carbon (in the form of woody biomass) from forests through practice, it is naturally pit against the climate change solution of long-term carbon sequestration in vegetation, leading to reluctance to implement fuel treatments. There are two main disadvantages to the practice of fuel management activities: 1) carbon in wood products is removed from the forest and 2) the activities can generate carbon emissions from the prescribed fires and the decay of leftover forest products on the site. Some interest groups even believe that the removal of wood products via mechanical thinning is just a veiled way to expedite timber harvest (Martinson and Omi, 2003). Although fuel treatments are intended to reduce the risk of severe wildfire and its associated emissions, implementing treatments that remove live and dead woody biomass that would be burned in a wildfire also reduces the amount of stored carbon in the forest. This issue leads to competing goals of removing carbon for fire protection which would potentially avoid large emissions events and sequestering carbon in forest biomass. There are many recent studies that focus on this relationship between carbon sequestration and fuel treatments, but few have been able to examine it over a long period of time with explicit quantification of treatment effectiveness (Saah et al., 2012). In addition, direct and delayed carbon emissions could occur from fuel treatments or the associated fuel treatment activities such as prescribed burning and biomass transportation. This is why carbon accounting in this context is very complex; the potential carbon impact is strongly dependent on the ratio of the carbon removed by fuel treatments to the reduction in carbon emissions from said fuel treatments (Ager et al., 2010). Prior studies have shown both positive and negative carbon outcomes between fuel treatments and wildfire (Ager et al., 2010). If forest management is solely focused on carbon accounting, of course they would prefer not implementing fuel treatments, but carbon is not the only factor when considering these types of activities (Chiono et al., 2017).

Overall, there is a general agreement among published literature that fuel treatments, such as thinning and prescribed fires, do reduce potential fire severity under a range of weather conditions. According to the Spatial Informatics Group, fuel treatment maintenance could theoretically extend greenhouse gas benefits by keeping fire size reductions high and creating additionality from wood products and biomass energy production (Saah et al., 2012). Expectations of fuel treatments can be kept pragmatic if they are seen as a means to help restore forest ecosystems and allow fire to play its natural role in forests (Reinhardt and Holsinger, 2010). Fuel treatments are recognized as an important tool for fire protection and ecosystem service restoration, but strongly developed strategies for implementation in different landscapes and vegetation types are still under way.

Avoided Wildfire GHG Emission Framework

How a framework is developed

To build out an avoided wildfire GHG emissions framework that would be effective for forest and fire managers, one would need to set up an integrated approach that considers wildfire probabilities, expected emissions, and net expected carbon sequestration or loss over time (Saah et al., 2012). Characterizations of forest growth (such as forest composition, structure, and fuels), fire behavior models, and the size and shape of the area must also be identified to perform this type of assessment. The Spatial Informatics Group, an environmental consulting organization, has developed a conceptual framework for estimating potential wildfire emission reduction credits for a particular fireshed. Figure 9 shows the major elements of their methodology.

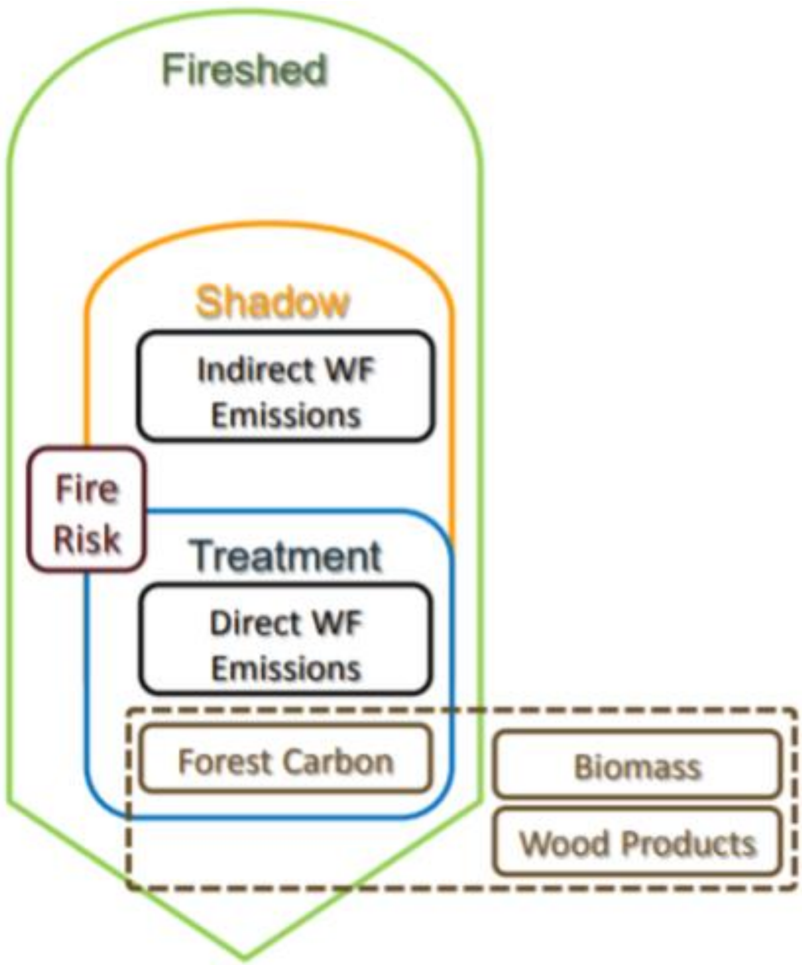

Figure 9. Conceptual Framework. Source: Saah et al., 2012

The major elements are defined in Table 3. This framework was designed to be in line with standard carbon market accounting principles used for determining credits.

Table 3. Major elements of a conceptual framework for estimating potential wildfire emission reduction credits Source: Saah et al., 2012	
Fireshed	An area of land of scale that allows the ecologically relevant integration of wildfire risk, wildfire hazard, and forest carbon accounting.
Forest Carbon	The sequestration of carbon in biomass (plant or tree trunks, branches, foliage, or roots) or soils through photosynthesis and growth over time.
Wood Products and Energy Production Benefits	Can be a substantial amount of biomass removed from the fireshed during fuel treatments.
Fire Risk	Used to discount the potential wildfire emissions savings from a given fire by the probability of the fire occurring.
Direct Wildfire Emissions Benefits	The emissions observed or expected to be reduced for each unit of area on the landscape.
Treatment Shadow	An area outside of fuel treatments that experiences altered or reduced fire behavior as a result of the treatment.
Indirect Wildfire Emissions Benefits	The reductions in emissions realized due to the treatment shadow effect.

An integrated framework that takes into account numerous factors and process-based models would provide localized estimates of potential relative emissions reductions. The recommendations that come out of such a framework can help forest managers offset fuel treatment costs with revenue generated from offset programs.

Challenges to framework development and implementation

The concept of carbon accounting itself is very straightforward, you record the sources and sinks of carbon, but the actual quantification of carbon stocks at a landscape scale is very complex due to many other factors such as spatial and temporal trends, interactions, and feedbacks from ecosystem processes. Wildfires are a great example of how complex carbon accounting can get; they are a necessary disturbance process in many ecosystems but can quickly become uncontrollable and do more harm than good if certain landscape or weather conditions are present.

Another big issue is leakage; leakage is when emissions end up moving to other areas as a result of implementing a project (CARB, 2019). One example would be implementing a harvesting project but cutting fewer trees within that project in pursuit of decreasing the amount of carbon lost; this premise could potentially increase demand for wood products and thus cause an increase in harvesting in another area. There are two main types of leakage: activity-shifting leakage and market-shifting leakage (CARB, 2019). Activity-shifting leakage is when the activities are shifted from inside to outside the project boundary. Market-shifting leakage is when a project affects market demand and ends up increasing activities outside of the original project boundary, similar to the example before. It is very important to account for and minimize leakage in the pursuit of climate policy development, but there is still a need for further research on what degree of consequence leakage can have on carbon (Cameron et al., 2017).

There will always be tension between dealing in business and working towards conservation objectives; a successful forest carbon project would ideally create healthy forests while being away of principles that govern business transactions in general, such as the way buyers and investors account for and mitigate risk, but the way risk is perceived can be two very different things to a business person and a conservationist (Covell, 2011).

Total Addressable Market Analysis

When launching into a total addressable market analysis for fuel treatment projects in California, four major factors need to be identified: 1) what does the marketable landscape look like, 2) how much of the marketable landscape can be utilized, 3) what are the cost assumptions, and 4) who are the stakeholder groups that will benefit or support from this type of project.

Fuel Treatments on California Biomes

California's natural and working lands, almost one-third of the entire state, have the potential to sequester carbon, reduce GHG emissions, and increase the ability of California to deal with impending climate impacts, which makes them a critical part of California's diverse climate change strategy portfolio (Forest Climate Action Team, 2018). Fire has always been a natural part of California's landscape; many of these ecosystems have adapted to fires as a main source of disturbance. Native tribes in California have used fire to manage landscapes for thousands of years, but as industrialization and urbanization increased, so did the desire and ability to suppress fires (CARB, 2019). Fire suppression has been observed to lead to landscapes that are misaligned with their natural state, increasing the risk of high severity wildfires that end up emitting enormous amounts of GHGs (CARB, 2019). The western United States semi arid forests have dealt with a century of fire suppression which has led to fuels accumulating to unacceptably hazardous levels (Campbell et al., 2012). As land managers continued to remove fire from the landscape, forests that experienced fire frequently began to miss Fire Return Intervals (FRI), which are fire cycles that would occur approximately every ten years (Forest Climate Action Team, 2018). As more FRIs continued to be missed (many have missed five or more natural cycles by now), dead material would pile up and fire-adverse species would move in creating biomass buildup and a species change that may result in a homogenous landscape with few niches and increased fire severity (Forest Climate Action Team, 2018).

Forest management activities in California are currently undertaken or funded by federal and state agencies including:

- Natural Resources Conservation Service
- CALFIRE
- California Department of Parks and Recreation
- California Department of Fish and Wildlife
- Sierra Nevada and California Tahoe Conservancies

Figure 10 maps out the many different sources of land ownership across California as of 2018, demonstrating how complex and expansive land ownership can be within the state. In California, the United States Forest Service (USFS) is the largest manager of forested land and they are aggressively pursuing ways to reduce the costs of fuel treatments, demonstrate its benefits, and enable markets for ecosystem services that would benefit from such treatments (Saah et al., 2012).

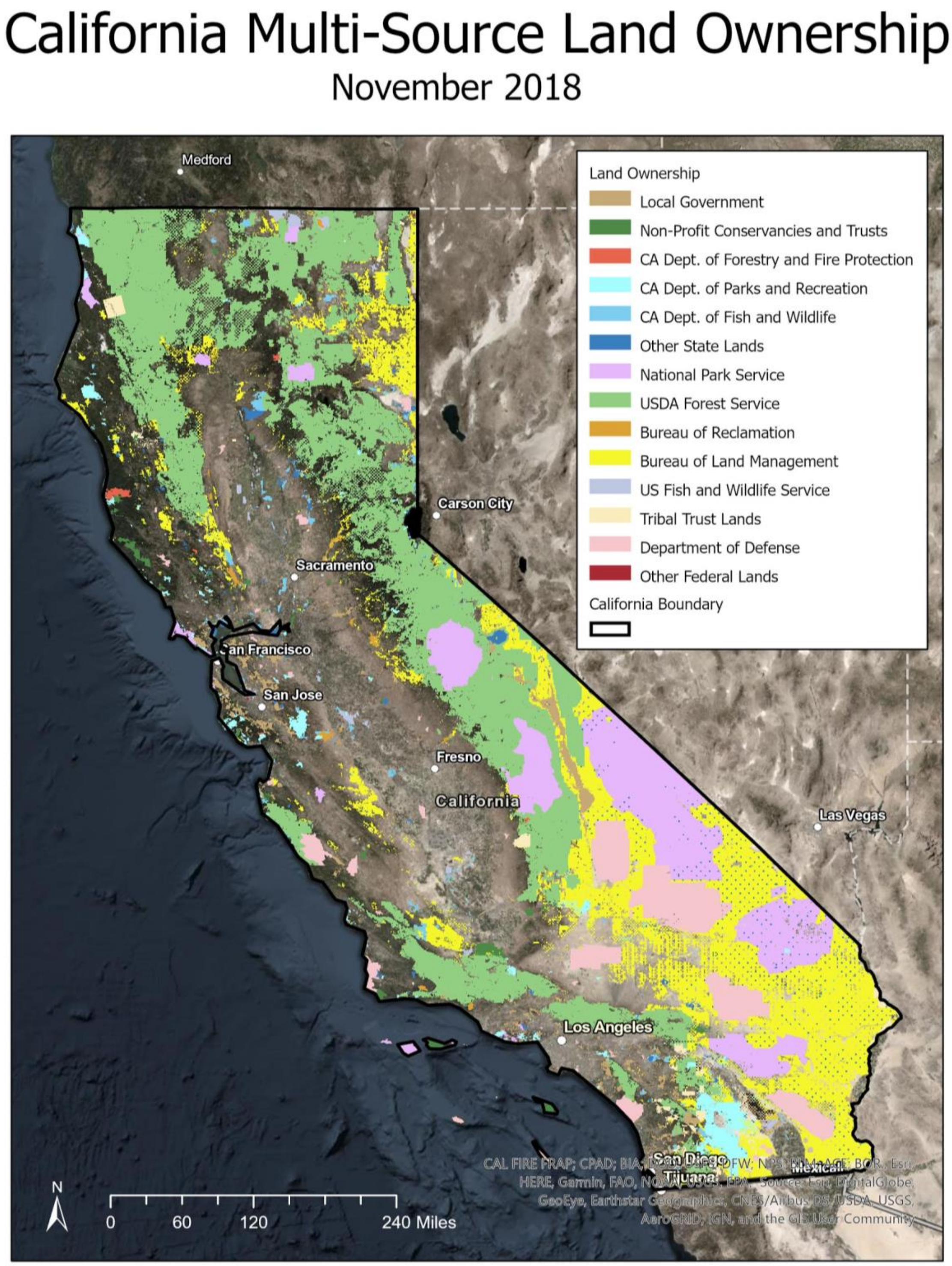

Figure 10. Multi-source Land Ownership in California, November 2018. Data source: CALFIRE

There are many factors to consider when deciding what fuel treatments will be applicable where, and how much it will cost to implement those particular treatments. The potential for emission reductions in different locations with different vegetation types must be identified. Western forests in general have great potential to sequester large amounts of carbon in the form of woody biomass; productivity generally exceeds decomposition in most of the West, so surface fuels tend to increase in the absence of disturbance, but if the forest has high density and understory the fire hazard also increases, so taking into account the landscape and different forms of forest in California is key in effective fire management. Higher tree density means that competition for scarce resources increases, stunting individual tree growth rates and thus sequestration rates; if stands can have reduced tree competition from the application of fuel treatments, they can experience better growth rates and allow carbon sequestration rates to also increase over time (Forest Climate Action Team, 2018). There are many different types of ecosystems in California that all contribute varying degrees of fuels and require their own unique fire management protocols.

California Ecosystems

Mixed conifer forests are one of the most dominate forest types in California; they are full of large trees on a landscape that stores more carbon now than they did in pre-European settlement times due to its increased tree densities, but even though it technically has more overall carbon now, a lot of this carbon is stored in the higher density, smaller fire-prone trees (Forest Climate Action Team, 2018). Mixed conifer forests hold the greatest amount of carbon in California out of all of California's forest types, followed by western oak forests and fir/spruce/mountain hemlock forests (Saah et al., 2016).

Coniferous forests generally have higher amounts of canopy fuels when there is less disturbance and more shade-tolerant trees become established which is great for carbon sequestration but worrisome if a wildfire occurs (Reinhardt et al., 2008). Although wildfires tend to only affect a small fraction of California's land area, they still account for a disproportionate amount of the state's carbon stock decrease (Gonzalez et al., 2015). Conifer forests have been found to have increased surface and ground fuels due to an increase in small-diameter trees across the western United States; these increases are likely to have contributed to the increases in uncharacteristically large and severe wildfires (Gonzalez et al., 2015). The amount of biomass fuel consumed in a fire is proportional to the degree of emissions released, and areas with forest or woodland vegetation types have greater fuel densities than lands with shrub, herbaceous plants, or grass vegetation types (CARB, 2020). Some examples of high carbon density forests included Redwood, Sequoia, Kings Canyon, and Yosemite National Parks (Battles et al., 2013). When assessing the application of fuel treatments in California ecosystems, the first step is to look at how much forested land would be in need of these activities.

Fuel Treatments in California Market

Market size

According to Malcolm North and his colleagues, it is estimated that under current legal, operational, and administrative constraints, 25% to 70% of forestland is available for mechanical treatment in a given California National Forest (Forest Climate Action Team, 2018). This range is considerably broad; constraints such as slope, distance to a road, and whether or not an area is a sensitive species habitat can affect the use of mechanical treatment (Forest Climate Action Team, 2018). Prescribed fires have similar constraints to mechanical treatments in addition to the unlikely use of prescribed fires within the wildland urban interface (WUI) due to higher mortality risk (Forest Climate Action Team, 2018). Considerable implementation of fuel treatments within the WUI will undoubtedly have unintended consequences; as the risks of living in the WUI are lowered with increased fuel management, the desirability of living in the WUI will increase, which will lead to increased development and increased value of property (Rideout, 2003).

The first type of analysis conducted here is to establish the total addressable market (TAM). The TAM is the total amount of demand that exists in a market for a product or service; in this case we want to look at how many acres of forest in California are in need of fuel treatments. The general workflow of this TAM can be visualized in Figure 11, where we start out with the total number of forested land in California, narrow it down to the desired amount of land fuel treatments should be implemented in, incorporate the average fuel treatment cost per acre and average carbon credit value, to finally get to an opportunity cost in carbon credits for the application of fuel treatments in California.

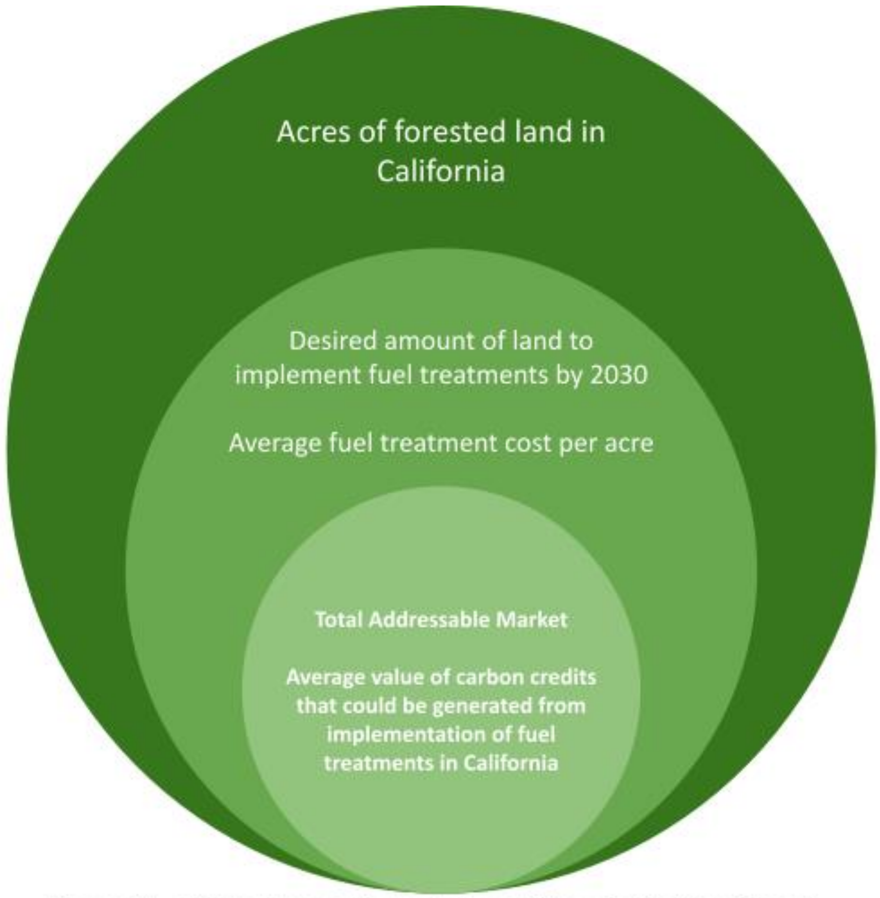

Figure 11. Total addressable market workflow for fuel treatment application in California

Table 4 shows us that based on both public and private landowners, there is a desired 580,000 acres to be treated each year with fuel treatments by 2030 - this is the number of acres that will be used to quantify the TAM.

Table 4. Forest Fuel Treatments in California by Land Owner in Acres. Source: Forest Climate Action Team, 2018					
Land Owner		Forest at Extreme Fire Risk (acres)	Fuel Treatment (acres/year)		Total Forestlands (acres)
			Current Baseline Business as Usual	Desired (by 2030)	
Public	US Forest Service	9,000,000	250,000	500,000	15,400,000
	Bureau of Land Management	1,000,000	9,000	20,000	1,500,000
Private		5,000,000	17,500	60,000	13,400,000
Total		15,000,000	276,500	**580,000**	30,300,000

Now that the number of acres desired to be treated in California has been established, the next step is to make some assumptions based on previous data, such as how carbon credits are produced per project acre, what are the typical fuel treatment costs, and how much are carbon credits even worth with these types of projects. Table 5 shows us that fuel treatment costs per acre varies greatly depending on the type of prescription, forest, terrain conditions, and the availability of markets for potential wood products.

Table 5. Assumptions and their Ranges. Source: Buchholz and Wack, 2020		
Credits per project acre (range)	5	15
Average credit volume per acre	7	
Typical treatment cost per acre (range)	$400	$3,000
Treatable acres of forest (Desired by 2030)	580,000	
Carbon credits value per ton ($/ton CO_2e)	$2.50	

From these assumptions, a valuation can be made to offer an idea of what the total amount of demand is for fuel treatments in California. This valuation can be found in Table 6.

Table 6. Total Addressable Market Valuation		
Estimated annual cost of fuel treatments	$232,000,000	$1,740,000,000
Total volume of credits generated (range)	2,900,000	8,700,000
Average volume of credits generated	4,060,000	
Total value of carbon credits generated (range)	**$7,250,000**	**$21,750,000**
Average value of carbon credits generated	**$10,150,000**	

Based on the calculations, it can be estimated that around $10 million in carbon credits could be generated from the application of fuel treatments across 580,000 acres of forested land in California. This cursory analysis involves forested acres in California and important assumptions, but what about the carbon stock in the forests themselves? This is where a feasibility analysis may be more useful.

Feasibility Analysis

The first step to deciding whether or not a project is actually viable is to see how financially feasible it is from both a business and technical perspective. The goal is to understand the cost of implementing the activities of the project, which is foundationally driven by their opportunity costs (Marvin et al., 2018). An opportunity cost of an activity tells us how economically productive using that land through that activity will be. Undergoing an initial feasibility assessment allows for the gathering of basic information that is needed, what key uncertainties there may be, and serves as a starting point for the ongoing assessment of the project's viability before a decision is made to pursue or abandon the project (Covell, 2011).

The feasibility analysis outline that will be demonstrated is based on an analysis by Forest Trends, a non profit organization that utilizes finance for conservation. To implement a successful forest carbon project, the total amount of carbon in the project area must be estimated (CARB, 2019). The analysis includes inputs based in California and a conversion factor from the California Air Resources Board. Table 7 denotes the legend that will be used throughout the analysis.

Table 7. Legend for Feasibility Analysis	
	Input
	Calculation
	Output
	Adjustment (subtract)
	Final Valuation

The flow of the analysis begins in Table 8 with a carbon stock calculation using the area average carbon density in California and the desired area of land to treat fuels from the previous TAM analysis. We then have the amount of carbon stock on the land that is desired to be treated. We convert that carbon stock to carbon dioxide foregone and then apply wildfire emissions rates and carbon stock reduction rates to calculate the baseline annual emissions from that area of land.

Table 8. Carbon stock and baseline emissions calculation in California		
Conversion factor (CARB, 2018)		
1	MT C lost	
3.7	MT of CO_2 forgone	
Carbon stock calculation		
1364.0196	MT C / acres	*Area-average carbon density; forest and other natural lands total (live and dead pools, not including soil, 2014); 552 MT / ha (CARB, 2018)*
580,000	acres	*Desired area of land to treat fuels by 2030 in California (Forest Climate Action Team, 2018)*
791,131,368	MT C	*Carbon stock*
Carbon to carbon dioxide conversion		
791,131,368	MT C	*Carbon stock*
2,927,186,061.60	MT CO_2	*Carbon dioxide foregone*
Baseline emissions calculation		
2,927,186,061.60	MT CO_2 / year	*Carbon dioxide foregone per year*
10%	%	*Wildfire emission rate per year; average rate in California (Global Fire Emissions Database, 2020)*
70%	%	*Carbon stock reduction after wildfire; released C per unit area (Campbell et al., 2012)*
204,903,024.31	MT CO_2 / year	*Annual emissions*

The number of emissions is further whittled down in Table 9 with rates such as the effectiveness of fuel treatments, permanence risks, and leakage risks, until the valuation of the area is finally reached.

Table 9. Adjustments to be made to the calculation due to permanence risk and leakage.		
Calculation of emissions reductions		
204,903,024.31	MT CO_2 / year	*Annual emissions*
13.2%	%	*Effectiveness of fuel treatments; effects of fuel treatment on fire size has a mean of 13.2% reduction (Thompson et al., 2013)*
27,047,199.21	MT CO_2 / year	*Emissions reductions per year*
Adjustments to determine marketable emissions reductions (buffer)		
20%	%	*Buffer (permanence risk) (Forest Climate Action Team, 2018)*
5,409,439.84	MT CO_2 / year	*Buffer (permanence risk)*
Adjustments to determine marketable emissions reduction (leakage)		
20%	%	*Leakage (Forest Climate Action Team, 2018)*
5,409,439.84	MT CO_2 / year	*Leakage*
16,228,319.53	MT CO_2 / year	*Marketable emission reductions*

Using the same price assumption per ton of carbon as the TAM analysis, and including an assumed sales commission, the opportunity cost per year for fuel treatments in California is finally reached in Table 10. In the carbon market there are those who matchmake buyers with sellers of carbon credits but do not buy the credits themselves, also known as brokers. These brokers typically get a commission for their work of around 3-8%, depending on the range of services they provide (Covell, 2011).

Table 10. Valuation of carbon credits with further adjustments, leading to a final opportunity cost for fuel treatments in California.		
Valuation		
$2.50	$ / ton of C	*Price assumption per ton of carbon; worth; (Buchholz and Wack, 2020)*
$40,570,798.81	$ / year	
Adjustments to valuation (sales commission)		
8%	%	*Sales commission; typically 3-8% (Covell, 2011)*
$3,245,663.91	$	*Sales commission*
Adjustments to valuation (government share)		
0%	%	*Government share; 0 because voluntary carbon offset*
$0.00	$	*Government share*
$37,325,134.91	$ / year	*Net amount available for fuel treatments; opportunity cost*

This feasibility analysis includes similar components to the TAM analysis, but involves much more thoroughly researched inputs such as carbon stock and recent rates to reach a more "accurate" final number. Compared to the TAM analysis, this feasibility analysis shows us that there may be over $27 million more of an opportunity cost available in California within this market.

To further assess whether a project is viable or not, the cash flow and analyses done above become the foundation for creating a financial model in which a project developer would incorporate and calculate items such as revenue, cost, returns, and carbon credits into a spreadsheet. Developing a financial model would allow for a dynamic understanding of the factors that determine whether or not a project should move forward. If a project is determined to be viable, more detailed financial analysis would occur to guide other business decisions such as investment and commercialization (Covell, 2011).

When analyzing project viability, it is very important to look at it from a conservative standpoint and be realistic; during the early stages projected benefits from these types of carbon projects are almost always overestimated while implementation and transaction costs are often underestimated (Covell, 2011). Transaction costs are the cost of doing business and are usually limited to the certification of the project and the matchmaking between sellers and buyers (Milne, 1999). Even if transaction costs are expected to decrease as time goes on due to standardized procedures and developed markets, there will always be a lot of uncertainty and risk when it comes to investing in forest carbon projects which will continue to constrain the size of this carbon project market (Milne, 1999). The voluntary market has always had a high degree of differentiation, which can have big effects on prices, how risk is allocated between buyers and sellers, and the financial structure of the associated projects (Covell, 2011).

Discussion

Costs for fuel treatments vary greatly and depend on the type of prescription, forest, terrain conditions, and the availability of markets for potential wood products. When it comes to the wood products being removed, the material tends to be of low quality and value, which makes this material a liability from both a fuel hazard and financial standpoint (Lynch and Mackes, 2003). The complete treatment of an entire area is not actually desirable, let alone financially feasible (Saah et al., 2016). If the market is not utilized, the alternative is to use millions of taxpayer dollars to implement fuel treatments and wage expensive and dangerous battles against increasingly large and destructive wildfires that severely damage ecosystems and impact human health and development (Lynch and Mackes, 2003).

There is a high amount of differentiation between forest carbon offsets in voluntary markets, which means that there is no one price that can be applicable to the many different types of projects or even within one project type. There are many different factors that affect the price of a carbon offset including: risk level, timing of the sale and payment, volume of credits sold, and the carbon accounting standards used (Covell, 2011). In addition to high variability in assumptions, there can also be a stark difference in estimated and perceived opportunity costs, which can complicate a financial analysis even further. These issues make it very difficult to be accurate in calculations, but ultimately decisions will be made based on perceived project benefits.

In reality, there are not many established mechanisms for cost recovery of fuel treatments; return on investment for fuel treatments would primarily come from avoided wildfire and its associated emissions, but even those quantifications are yet to be strongly validated (Saah et al., 2016). To demonstrate value in implementing fuel treatments, outside investment or even converting biomass into valued products needs to occur to help reduce future treatment costs while decreasing the effects of high severity wildfire.

Organizational Partnerships / Support

There is a large misconception that because forest carbon projects have a lot of appealing factors, they can easily sell on the market. Unfortunately this is not true; the circle of forest carbon buyers tends to be small and particular about what kinds of forest carbon offsets they want to purchase (Covell, 2011). Just like any other economic activity, to create solid carbon revenue a forest project must be planned and executed well, either through public expenditures or private markets.

In the past, the largest supporter of forest carbon projects have been the governments those projects reside in; the carbon market has played a smaller, but still critical, role with these types of projects (Covell, 2011). Support for carbon projects can be broken down into three main categories: market support, government support, and civil society support. The market includes businesses and corporations that help take on high volumes of carbon credits at lower implementation and transaction costs to create financial viability. Government support involves the public sector working with public land to work towards generating public good. Civil society, the not for profit but non-governmental source of support, includes private organizations and non-governmental organizations (NGOs) that offer lower amounts of funding but can provide legitimacy and leverage to work towards positive environmental and social impacts. Table 11 outlines in more detail how these three sources of support can be broken down within the carbon market.

Table 11. Conditions Favoring Market, Government, and Civil Society Support. Source: Covell, 2011			
	Market Support	**Government Support**	**Civil Society Support**
Project Characteristics	High volume of carbon credits (large area of land, large carbon stocks under identifiable threat, approved methodology)	Involves public land (or government asserts carbon rights, regardless of land tenure)	Small scale
Project Impacts and Co-benefits	Complementary revenue streams (timber, NTFPs, tourism, and other non-carbon products may be key to financial viability)	Generates a public good (fulfills the mission of a public-sector agency that champions the project)	Highly positive environmental impact (especially biodiversity) Highly positive social impact
Cost of Abatement	Low cost of abatement (implementation and transaction costs)	Moderate cost of abatement	Moderate cost of abatement
Policy Environment	Market-friendly Low legal and regulatory risk	Supportive policies on PES (political decision to value ecosystem services, budget availability)	Strategically leverages public policy reforms or market support
Agency	Corporate champion	Public sector champion	NGO champion

Access to donor resources are becoming more and more critical for forest carbon projects to get off the ground; there are many financial and market challenges these types of projects face, and in a lot of cases carbon revenue alone won't be enough to sustain this type of work (Covell, 2011). To develop complementary revenue streams for projects, additionality must be proven. Additionality is the concept of showing that this carbon project would not be feasible on just carbon revenue alone, and that additional investment or revenue is needed to make the project happen.

To create enthusiastic buy-in, the project must generate market value, be supported by a clear accounting methodology, and meet specific needs or objectives. Corporate social responsibility (CSR) is an increasingly trendy type of value of potential buyers may even deem worth more than the actual carbon sold - CSR is a way for businesses to contribute social good by participating in charitable or ethical practices, including investing forest carbon offsets (Covell, 2011).

Anticipated Outcomes and Benefits

In addition to assessing the financial feasibility of the avoided wildfire emissions framework in California, there are many other benefits not included in the assessment that would help make fuel treatment activities more cost-effective and favorable.

Environmental

With years of fire exclusion occurring in California on top of drought and climate change, wildfires have increased in size and intensity, bark beetle infestations have grown, and public health has been highly threatened. These are just some of the environmental reasons why managing forests has become a vital part of California's climate change policy (CARB, 2017).

Climate change is expected to extend drought and cause earlier snowmelt in California; southern California in particular is expected to see 30% drier and 2 degrees Fahrenheit hotter conditions over the next 15 years (Forest Climate Action Team, 2018). Factors such as increased fuel growth from a previously wet winter, extreme multi year droughts increasing the amount of standing dead fuels, record warmth, significantly light amount of precipitation, and extended high wind events are all expected to become more common in a future of climate change (Westerling, 2018). Continued research on these factors and their effects on fire events will help improve decision making and plan for more fire-safe communities. It can be expected that climate change impacts will dramatically change California vegetation in ways still unknown (Westerling, 2018).

With climate change at the forefront of many environmentalists' minds, there is yet to be a climate model that accurately enough projects fire weather conditions; this is why strategically implementing fuel treatments will allow forests to be more resistant to the changing climate and the unknown ways climate change may affect them (Stephens et al., 2009).

Decreased wildfire risk

Decreased wildfire risk is largely motivated by the concept of community protection. The community protected in this case includes (Finney and Cohen, 2003):

- The environment (and it's scenery, air quality, water quality, and wildlife)
- Structures, neighborhoods, and businesses
- Infrastructure (such as roads, bridges, dams, etc.)
- Lifestyle and economy (including recreation, agriculture, and other industries)

GHG Emissions

Climate change is expected to continue to exacerbate the existing stressors that are currently on the state's forested landscapes – wildfire emissions, including carbon dioxide, carbon monoxide, and particulates such as black carbon, are estimated to increase (Forest Climate Action Team, 2018). Black carbon is incredibly dangerous to human health and can cause cardiovascular and respiratory disease; unfortunately California wildfires are the largest source of black carbon and an average wildfire season can contribute up to two-thirds of the black carbon emissions in the state (Forest Climate Action Team, 2018). If land managers continue business-as-usual and global GHG emissions are not decreased, there will likely be a significant increase in wildfire smoke in California, leading to a multitude of health impacts (Forest Climate Action Team, 2018). In addition, if business-as-usual continues for emissions outside of forests, such as fossil fuel burning from cars and power plants, climate change may increase wildfire frequencies by ⅓ to ¾ across California (Gonzalez et al., 2015).

Of the estimated 150 million metric tons of carbon lost from California forests between 2001 and 2010, roughly 120 million metric tons of that carbon was lost through wildfires (Forest Climate Action Team, 2018). Wildfires are the single largest source of GHG emissions from forested lands which is why reducing the intensity and extent of these wildfires through fuel treatments should be a top priority for land managers.

Recommendations

Entering the Market

Even if the cost of business in carbon markets go down over time, processes become more simplified and standardized, and carbon markets develop, investing in forest carbon projects will continue to have uncertainty and risk associated with them that will continue to constrain the size of the forest carbon project market (Milne, 1999). This is why there is still a need for substantial funding for these types of projects, especially to initiate them. Transaction and implementation costs will continue to be high, especially with smaller-scale projects, so investment from external resources is necessary.

When entering the market, it is very important to develop the model and plan at the local scale to make the fuel treatments most effective in that area; this includes understanding the local topography, vegetation, and weather patterns, incorporating those into the predicted fire behavior, and then designing treatments ideal for mitigating wildfire risk in that area (Saah et al., 2016). This will allow for more effective and tailored strategies that fit within land managers' economic constraints and acceptable levels of risk; strategic fuel treatment activities are likely to be more effective when land and fire managers' knowledge and experience are incorporated into the treatment considerations (Stephens et al., 2009).

Businesses should invest in natural climate solution offsets such as fuel treatment activities for multiple benefits: they are able to do so ahead of impending government regulations, build up practical experience in pursuing investments such as these, contribute to the development of this industry's infrastructure and market design, and build networks and expertise to thrive in this carbon market (Webb and Zakir, 2019).

Biomass Utilization

To take advantage of the biomass that is discarded from the application of fuel treatments, regional infrastructure should be set up to transport and utilize the forest material. Forest waste material could be used to create durable wood products, animal feed and bedding, biofuels, compost and other soil amendments, and many more (CARB, 2017). This will allow for sustainable forest management, minimized GHG and black carbon emissions, and growth of utilization markets and economic development. The state of

California could also have a hand in developing incentives to support these types of markets for the wood material; the creation of a well-designed wood materials sale would be an economical opportunity for an agency to use for fuels removal if there is a market for such products and processing facilities are nearby (Lynch and Mackes, 2003). With the increasing size and costs of destructive wildfires, the question of what to do with excess fuels persists. A potential market solution for this problem involves researching ways to develop efficient harvesting systems, what kind of products could be made with this wood material, and what market channels are available to produce revenue that could offset the original treatment costs (Lynch and Mackes, 2003). In addition, utilizing forest biomass could help reduce the cost of implementing fuel treatments and reduce the carbon loss associated with fuel treatments (Chiono et al., 2017).

There are numerous climate benefits to using wood products after harvesting: in 2011 woody biomass was the second largest source of renewable energy in the United States and there is abundant research that shows using wood over steel or cement in buildings can help reduce the total amount of energy a building uses (Stewart and Nakamura, 2012).

Centralized Database of Forest Management and Conservation Activities

Among the federal and state agencies in California that are responsible for managing the forests, there is currently no centralized database of forest management or conservation activities that have or will be taking place (Forest Climate Action Team, 2018).

A large hurdle to understanding fuel consumption and accurate GHG emissions from forests is the lack of pre- and post-wildfire field data (Saah et al., 2016). Different agencies have different databases with different information of priority, for example, CAL FIRE uses CalMAPPER, a database with information including timber harvesting plans, forest improvement projects, and fuels reduction, whereas CARB has a database of forest carbon offset projects and California Climate Investment projects. With so many different types of data coming from different places, it is easy to understand why forest managers continue to face "analysis paralysis" which is when there's an overload of data that makes it difficult to analyze effectively (Ingalsbee, 2003). In addition, many of these databases are not designed to offer data on expected carbon stock of GHG emissions associated with forest management and conservation activities, which forces methodologies using avoided wildfire emissions to rely on assumptions that tend to lack empirical data (Saah et al., 2016). The transparency and alignment of data between agencies is lacking, which is why developing a centralized database that can standardize data from the many different sources would be an incredibly useful way to track progress and link policies, programs, and funding sources to actual outcomes of conservation.

Long Term Monitoring

Although the short term effectiveness of fuel treatments has been well studied and documented (short term as in 1 to 2 years), longer term effectiveness is yet to be well understood. Effectiveness of fuel treatments would be measured by how well it reduces fire behavior and its effects, depending on multiple factors such as fuel accumulation and distribution (Vaillant et al., 2012). Since there is not much information on effectiveness on a longer time scale, it makes it more difficult for planning fuel treatments. This is why more monitoring of fuel treatments before and after the treatment is put in place across the various agencies would help them understand how to better manage forest structure and how it changes over time.

Further Research on Carbon Dynamics

The relationship between fuel treatments, carbon, and wildfires needs to be further explored and simulated, especially in higher frequencies due to the increasing potential for wildfires (Chiono et al., 2017). A worthwhile analysis between carbon and fuel treatments would include variables such as fire probability, treatment longevity, and the issue of retreatment (Moghaddas et al., 2018).

Remote sensing of vegetation is a highly effective way to monitor carbon stocks, but even with quickly developing technology it is still difficult to accurately quantify carbon stock changes with remotely-sensed data since activities such as fuel treatments are periodic and the carbon stocks tend to recover at varying rates (Saah et al., 2015). This is why further research on carbon stocks and calibration between them, fuel treatments activities, and other factors like land ownership type and temporal lag, are needed to advance the understanding of carbon dynamics in forests.

Public Understanding

The sustainability of fuel treatment programs rests on public understanding and acceptance of such programs. Public understanding of fires and fuel treatments tend to be based on recent events, which is why context surrounding fires and fuel treatments is incredibly important to communicate. The Forest Service continues to deal with a large amount of public controversy created by their management proposals, and when the Forest Service is met with public opposition against a decision, it can be misinterpreted as opposition against all forest management in general (Ingalsbee, 2003). The way the public understands their surrounding ecosystems has a huge impact on the objectives, strategies, and actions they implement to reduce wildfire risk and attempt forest restoration. Landowners and communities who are directly affected by forest fires have on-the-ground insight as to when and where fuel treatments should be implemented, leading to valuable sources of decision-making information. Decision-making in this realm requires a careful integration of science and public values to avoid "analysis paralysis" and to move towards collaborative approaches that address the root of problems such as unhealthy forests and fire risk (Cheng, 2003). Unfortunately, collaboration is easier said than done; these types of efforts are incredibly time consuming and can lead to high expectations but low results, but this does not mean the effort is not worthwhile. Collaborative processes can help determine the most suitable times and places for fuel treatments, and with such wide support the implementation process could be much smoother. A collaborative planning process can also help build economic capacity to reduce and utilize removed fuels, and address long-term conservation on a larger scale. The ultimate goal is to build "new forms of problem-solving relationships" in which the public can engage with local natural resource issues and objectives (Burns et al., 2003).

Conclusion

This is an incredibly difficult matter that is challenged by high treatment costs, accessibility to resources, and large spatial scale in need of operations. It does not matter if California's firefighting budget increases or fire prevention efforts increase, wildland fires cannot be stopped; they will always occur and for many ecosystems they need to occur, so attempting to stop them is futile (Finney and Cohen, 2003). This is why the true challenge for forest managers is to refocus their efforts on lessening the undesirable impacts of fires on ecosystems and human development, rather than attempting to stop fires altogether.

Forest managers do not have any control over topography or weather; the ability to modify fuels across large landscapes can change the probability of fire impacts and increase the safety and well being of forests and the public. As a whole, fuel treatments are meant to offer benefits that encompass lesser carbon emissions, lesser losses of biodiversity, and lesser threats to communities, and if fire suppression and other landscape disruption is prioritized over strategic precautions such as fuel treatments, then forest resources will just be more vulnerable to catastrophic fires and extreme conditions will continue to develop. The longer these fuel treatment activities are delayed, the higher the cost of abatement in future years will become and the higher the speed that is necessary for decarbonization, "risking economic disruption." With such ambitious goals set by California to decarbonize, fuel treatment application through the use of carbon offsets, although not a long-term solution to climate change, can offer critical assistance in the meantime and is worth the investment.

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